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A SIMPLE MACHINE FOR ISENTROPIC COMPRESSION EXPERIMENTS (ICE)

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Abstract. A single-turn magnet pulsed power system, at the Los Alamos National Laboratory (LANL) National High Magnetic Field Laboratory (NHMFL), was originally designed to measure actinide samples in extremes of high magnetic field (to 300 Tesla) [1, 2]. A simple modification to the system has converted it to a fast turnaround, inexpensive, magnetic system for Isentropic Compression Experiments (ICE). For the design and predictions of performance of the NHMFL-ICE experiment a circuit code simulation was chosen to model all aspects of the experiment, electrical and physical. This paper describes the potential performance of the system, recent experiments, and plans for a portable system. The 2.2 μs rise time of the system allows sample thicknesses up to ~5 mm. With the present design the maximum stresses are ~50GPa (0.5 Mbar) at the maximum bank voltage of 60 kV.

Keywords: ICE, isentropic compression, capacitor bank, portable, SPICE.
PACS: 07.35.+k, 62.50.-p, 74.62.Fj.

INTRODUCTION

The NHMFL capacitor bank described here has been modified to become a low cost ICE machine for the acquisition of high accuracy, fast turnaround (i.e., many shots / day) EOS data and the study of phase changes in the range of 0 to 50 GPa. Stresses approaching 100 GPa may be obtained with modifications to the load.

The ICE technique was first demonstrated by Asay [4] on the Z-machine at the Sandia National Laboratory. In an ICE experiment, smoothly rising (shock-free) mechanical compression waves are propagated into matched samples of different thicknesses by electromagnetic loading in a planar geometry. A complete isentropic Equation of State (EOS) is acquired in one experiment, from zero up to the peak stress. ICE experiments are performed by depositing mega-ampere currents of *ca.* 1 μs rise time from fast capacitor banks [4-9] or by using high explosive techniques [3, 10].

Comparison of techniques

The predominant machine for ICE research is the Sandia Z-machine [4] which is capable of delivering currents of tens of MA with rise times of between 100 ns and 600 ns. Pressures of the order of 500 GPa on the Z-machine have been obtained but it is not portable and is expensive to operate.

Smaller capacitor banks have been designed specifically for smaller-scale ICE experiments, e.g., [6, 9], and these may reach pressures of the order of 50 GPa in approximately 500 ns, but even these machines are relatively expensive to manufacture. The explosive techniques can be used to produce ICE data at comparable or greater pressures than those on the Z-machine [11].

At pressures of a few hundred GPa the costs of these explosive experiments are comparable to those of the Z-machine, but the higher pressure experiments would be more expensive. The explosive ICE technique is preferred for: very high pressure experiments; the study of noxious materials that could contaminate capacitor banks and or the buildings that house them; and the performance of experiments in remote locations because the explosive experiments are portable and compact.

The NHMFL-ICE technique is an excellent method for measuring equations of state (EOS) at pressures below 1 Mbar. Many experiments can be

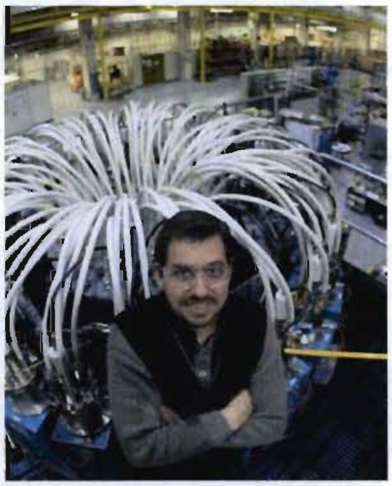

Figure 1. The NHMFL bank showing the cluster of coaxial cables connecting the bank to the load.

performed in a day, so the technique promises to provide high quality EOS data at low cost. The NHMFL bank in Figure 1 has a capacitance of 144 μF, a maximum voltage of 60 kV and a peak current of 4.5 MA. The discharge is sinusoidal with a time to peak of 2.2 μs and it uses coaxial cables to couple the capacitors to the load.

Accuracy of the various methods

It should be noted that the accuracy of the ICE technique depends primarily on the accuracy of the diagnostics e.g., VISAR [12], the quality and precision of sample preparation and time synchronization, and the uniformity of the magnetic drive. As all ICE techniques use similar diagnostics and sample preparation techniques, the accuracies of ICE data produced by capacitor bank or high explosive techniques are comparable [3].

Experimental technique

The basic compression mechanism for ICE is the magnetic loading of two or more identical samples of equal widths but *different* thicknesses, situated on the rear surfaces of a pair of parallel conductors. As the conductors carry current along their inner surfaces, magnetic compression waves are generated which traverse the conductors into the samples; they eventually breakout on the rear surfaces of the samples and the velocities of the surfaces are measured by VISAR or photonic doppler velocimetry (PDV) [12, 13]. Standard data reduction techniques, Lagrange or Backward [14], are then used to derive an EOS for the samples.

Reduction of stress rise time by rarefactions

The sample dimensions limit the duration of the stress on the load and hence the peak stress. The compression waves traverse the sample thickness and reflect at the outer surface. Consequently longitudinal relief waves are initiated at that surface, which then travel back to the slit surface, negating the compression on the way. When these relief waves return to the inner surfaces the stresses on the samples are reduced, even though the current flow may not have peaked. Similarly, lateral rarefactions from the outer edges of the width of the samples relieve the stresses.

As the samples have different thicknesses, the longitudinal rarefactions waves arrive back at the inner surfaces at different times. However, *it is essential that the samples are subjected to identical, simultaneous plane wave compressive loads for the ICE technique to be valid.* As soon as the first rarefaction waves arrive at the inner surface of the thinnest sample, the stresses in the two samples are no

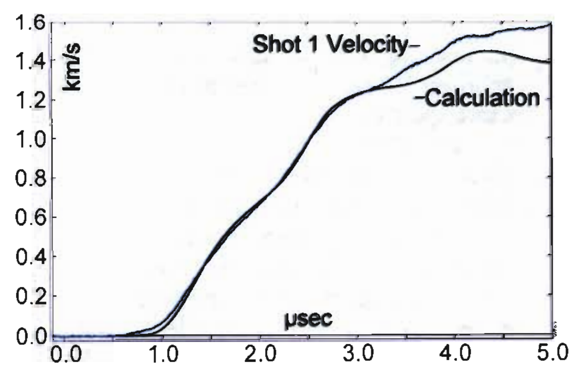

Figure 2. Comparison of predictions (bottom) of surface velocity and VISAR results (top) of the first experiment for 125-mil thick copper samples, 1 cm wide, bank voltage 35 kV.

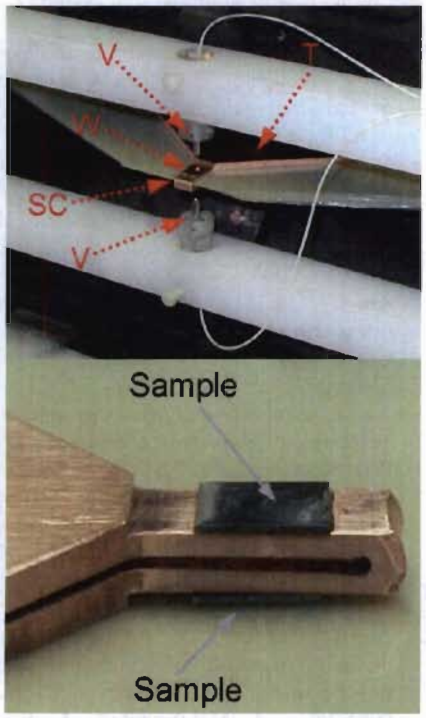

Figure 3. Top - load assembly showing: the copper tapered load (T); SC –the short circuit at the end of the load; V –the two PDV velocimeters; W - tungsten sample on top of the copper. Bottom – close-up of 1-cm wide electrodes with tungsten samples attached.

longer equal. This effectively terminates the experiment as no further EOS data may be obtained.

Numerical model for NHMFL-ICE

A novel circuit simulation code, dubbed "*sp*ICE," was chosen to predict all aspects of the experiment [15]. The plots in **Figure 2** are the experimental results and predictions for a copper sample in the first experiment which was nominally 3.15 mm thick, and 10 mm wide. Note the ringing of the surface velocities in the figure which is caused by the multiple wave reflections in the load. The rarefaction arrived at 1.8 μs, so the EOS data gathering portion of the experiment ended then. The calculations appear close to the measured surface velocities up to 3.2 μs when there is a significant divergence of the velocities; the cause is unknown. Before that time the differences between experiment and calculation are consistent with the estimated errors in measurement of a few percent.

Clearly the *sp*ICE model simulation of these ICE experiments produces good results. Note that any error in prediction does not affect the accuracy of the EOS data; these are derived directly from the experimental data using the methods described above. The *sp*ICE model calculations predict that stresses of 50 GPa can be reached with the present design of the NHMFL-ICE system.

Proof-of-principle experiments

A series of five low-budget experiments were performed to demonstrate the feasibility of performing ICE experiments on the NHMFL bank. The bank cables in **Figure 1** terminated in a short, tapered copper parallel plate transmission line. The ICE-load formed the narrowest end of the taper, Figure 3. For economy, the electrodes were made in one piece which made it impossible to accurately control and measure the electrode thicknesses. Consequently, these were *proof-of-principle* experiments, not EOS data-gathering experiments.

Four of the five experiments produced high quality velocity data; one failed because of a capacitor prefire. PDV velocity data for two copper samples (nominally 1.96 mm and 3.175 mm thick) are shown in Figure 4. The results were in good agreement with the *sp*ICE predictions up to 4.5 μs on the thinner sample, when it apparently accelerated; the cause may have been air flash.

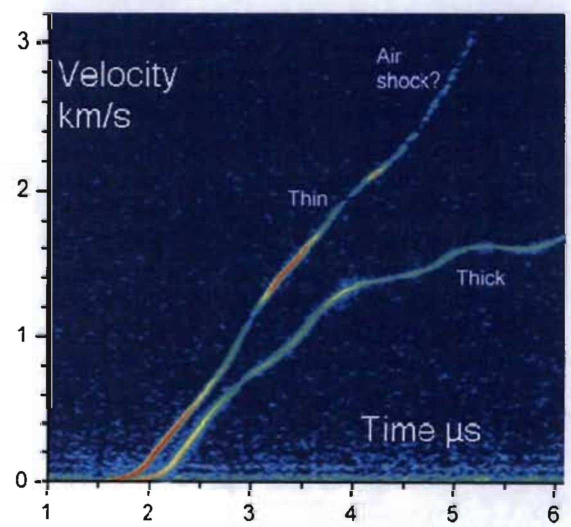

Figure 4. PDV velocity data for 1.96 mm and 3.175 mm thick copper samples.

DISCUSSION AND SUMMARY

Four successful experiments were performed which demonstrated the feasibility of the NHMFL-ICE technique. The measured velocities were close to the predicted values, i.e., within the estimated errors in metrology.

The NHMFL-ICE technique has been shown to be an excellent method for measuring high pressure EOS data at pressures up to 50 GPa and perhaps beyond with modifications to the load. Because a complete EOS can be obtained in one experiment from zero to the peak pressure, and because many shots can be fired in one day, the technique promises to provide high quality EOS data at relatively low cost; this makes ICE accessible to a broader scientific community. For example, this would allow the performance of ICE on geological materials to become economically feasible.

The NHMFL-ICE machine has a relatively long current rise time, which can easily be increased, so it would also be a powerful tool for measuring isentropic material properties at strain rates bridging the gap between Split Hopkinson Pressure Bar data 10^3/s and conventional ICE data (10^5/s to 10^6/s). Also, because the NHMFL capacitor bank is compact it is possible to transport it. ICE experiments could be performed at such locations as the Nevada Test Site; MaRIE, the proposed LANL Matter-Radiation Interactions in Extremes facility; the LANL proton radiography facility; and the ANL Advanced Photon Source.

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